EARTHQUAKE ENGINEERING AND STRUCTURAL DYNAMICS
Earthquake Engng Struct. Dyn. 2000; **29**: 177–193

Effective location of active control devices for building vibrations caused by periodic excitation acting on intermediate storey

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SUMMARY

In order to investigate ways of reducing vibrations of building structures subjected to excitation acting on intermediate storey, active vibration controls are conducted with active control devices installed on different floors of the structure, and the effective location of control devices is also investigated. In this paper, we propose a new 'Discrete-Optimizing Control Method' for vibration control. The control forces are determined analytically which makes the 'discrete-index function' minimum. Through numerical simulation, the Discrete-Optimizing Control Method is proved to be an effective control method. The response reduction effects are the best when the control devices are concentrated on the adjacent three floors of the vibration source. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: active vibration control; intermediate story; human movement; periodic excitation; discrete-optimizing control method

1. INTRODUCTION

The notion of structural controls currently defined can trace its roots back more than 100 years to John Milne, a professor of engineering in Japan, who built a small house of wood and placed it on ball bearings to demonstrate that a structure could be isolated from earthquake shaking. Though having its roots primarily in such aerospace-related problems as tracking and pointing, and in flexible space structures, the technology quickly moved into civil engineering and infrastructure-related issues over the past several decades. Much of structural control research in civil engineering has been directed toward structural response control against two kinds of external excitations: wind and earthquake [1–3]. Tuned mass dampers, either active or passive, or active mass dampers have been largely used to reduce the response of large buildings to wind excitation, and the use of isolation with passive or active damping in the building structure combines the ability to resist both strong wind excitation and strong earthquake excitation. In

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Received 6 April 1999
CCC 0098–8847/2000/020177–17$17.50
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Revised 30 June 1999
Accepted 31 July 1999

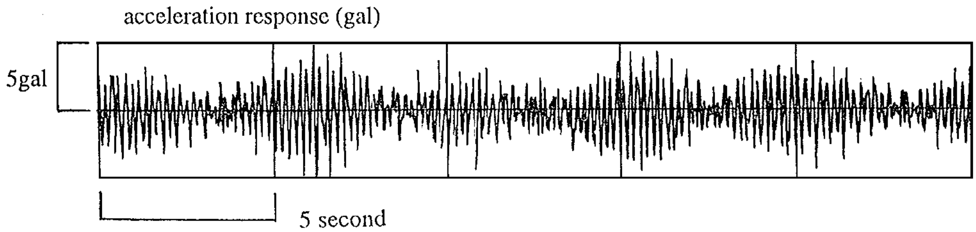

Figure 1. Observed time history of absolute acceleration response on the 15h floor of a certain 19-storey building in Japan.

Japan, over 400 base-isolated buildings and over 50 vibration-controlled buildings were constructed in the last decade.

On the other hand, in recent years many aerobic fitness clubs have been constructed in the intermediate storeys of tall buildings. Aerobic activities such as aerobic dance, step training, use of aerobic machines and so on naturally occur at these levels. Aerobic dance generally means a lot of people move to the same direction almost at the same time rhythmically. These days there seems to be an increasing number of cases in which the whole structure has horizontal vibrations due to this kind of human movement which occurs in intermediate storeys. In some cases, it does make people in the upper floors feel uncomfortable because of the vibration. Figure 1 shows the observed time history of absolute acceleration response on the 15th floor of a certain 19-storey building in Japan. The horizontal vibration is caused by aerobic movement occurred in the intermediate storeys of the building. The maximum absolute acceleration response is about 5 gal which is beyond the average value of human perception according to ISO 6897.

Though the response caused by this kind of excitation is practically becoming a problem currently, adequate research on the response of a whole structure based on the external excitation acting on the intermediate storey has not been actively carried out yet. In this paper, numerical analysis is carried out in order to investigate the effects on the response of a building with an active control system when external excitation occurs in an intermediate storey.

In civil engineering, most active control systems have been developed based on the linear-quadratic optimal control theory. When this theory is applied, the external excitation is assumed to be a white noise, at least, it has simple statistical characteristics [4, 5]. In the instantaneous optimal control method, such conditions are not required by introducing a time-dependent index function, but the required control forces which are regulated by the response may possibly exceed the capacities of control devices [6]. In this paper, a 'Discrete-Optimizing Control Method' is proposed and adopted to determine the control forces step by step [7]. The natural vibration characterization of the structure is kept constant and two kinds of excitation are used in the analysis. The effects on the response control reduction are examined and compared with the case when the vibration control device is not present.

2. CONTROL METHOD

Generally the studio floor where the aerobic dance occurs is constructed to be supported by air-cushion, in order to reduce the horizontal and vertical vibrations. But desirable response

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reduction cannot be obtained only with the constructed air-cushion. Considerable research about reducing vertical floor vibration has already been conducted [8, 9]. In this paper, only the horizontal vibration of the structure is discussed. The effect of human movements is supposed to be simplified as horizontal external excitation acting on an additional mass (Figure 2), and the external excitation is transferred to the main structure via the additional mass. The main structure and the additional mass can be modeled as a linear lumped mass system which is an n-storey structure with an additional mass on the ith floor (Figure 3).

Assuming that the lumped masses and the additional mass can only move horizontally, the whole structure can be simplified to have $(n+1)$ degrees of freedom Active mass damper (AMD), composed by AC servo motor and a ball screw shaft, is used to reduce the response of the structure. The informations of the vibrated structure (usually acceleration, velocity and displacement) are first measured by sensors, then, the computer defines the command signals according to the appropriate control algorithm and the desired control force is delivered to the auxiliary mass by means of the AC servo motor, finally the reaction for the inertia force of the auxiliary mass is

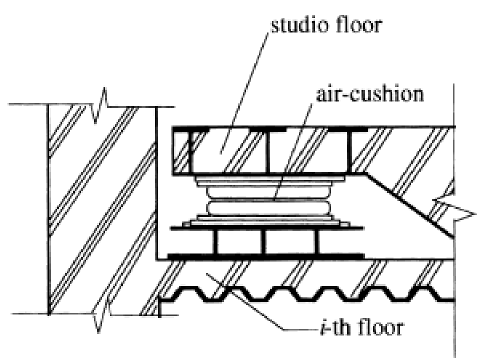

Figure 2. Schematic diagram of the additional mass.

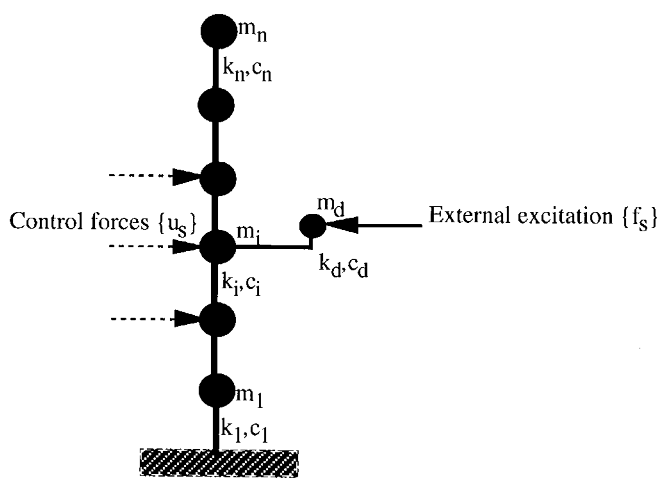

Figure 3. Analysis model.

actually acting on the main structure and eventually reduce the vibration of the main structure. In this paper, the control forces are determined by the Discrete-Optimizing Control Method.

The equation of motion in discrete time function can be expressed as

$$[M]\{\ddot{q}_s\} + [C]\{\dot{q}_s\} + [K]\{q_s\} = [U]\{u_s\} + [E]\{f_s\} \tag{1}$$

where $[M]$, $[K]$ and $[C]$ are $(n+1)\times(n+1)$ structure's mass, stiffness and damping matrices, respectively; $\{\ddot{q}_s\}^{\mathrm{T}} = \{\ddot{q}_{1,s}, \ddot{q}_{2,s}, \ldots, \ddot{q}_{1,s}, \ddot{q}_{d,s}, \ddot{q}_{i+1,s}, \ldots, \ddot{q}_{n,s}\}^{\mathrm{T}}$ which is an $(n+1)$-dimensional structure acceleration vector at the time instant of $t_s = \Delta t \times s$ (where Δt means a discrete control time interval and s is an integer number); $\{\dot{q}_s\}$ is an $(n+1)$-dimensional structure velocity vector; $\{q_s\}$ is an $(n+1)$-dimensional structure displacement vector; $\{u_s\}$ is an m-dimensional control force vector; $[U]$ is an $(n+1)\times m$ control force location matrix which is 1 or 0 depending on the presence or absence of the control devices; $\{f_s\}$ is one-dimensional external excitation vector; and $[E]$ is an $(n+1)\times 1$ excitation location matrix which is 1 or 0 depending on the presence or absence of the external excitation.

Let the state vector $\{X_s\} = \{\dot{q}_s^{\mathrm{T}}, q_s^{\mathrm{T}}\}^{\mathrm{T}}$, the equation of motion can then be expressed as

$$\{\dot{X}_s\} = [A]\{X_s\} + [B]\{u_s\} + [D]\{f_s\} \tag{2}$$

where

$$[A] = \begin{bmatrix} -M^{-1}C & -M^{-1}K \\ I & 0 \end{bmatrix}, \quad [B] = \begin{bmatrix} M^{-1}U \\ 0 \end{bmatrix}, \quad [D] = \begin{bmatrix} M^{-1}E \\ 0 \end{bmatrix}$$

In close-loop linear-quadratic optimal control method or instantaneous optimal control method, the control vector is regulated by the state vector and the feedback gain matrix. Therefore, the capacities of control devices may not always be guaranteed. In order to overcome such a practical problem, 'Discrete-Optimizing Control Method' is proposed.

In 'Discrete-Optimizing Control Method', we first assume that the control forces of each device at time instant t_s can be limited into a few kinds of trial control forces which can possibly be executed, such as $\langle \bar{u}_j \rangle$ for the jth device, where notation $\langle - \rangle$ represent, a 'set'. For instance, in the case that those control forces are limited into N_j kinds,

$$\langle \bar{u}_j \rangle = \langle u_{j,1}, u_{j,2}, \ldots, u_{j,a}, \ldots, u_{j,N_j} \rangle \; (u_j^{\max} < u_{j,a} < u_j^{\min}, \quad a = 1, 2, \ldots, N_j, j = 1, 2, \ldots, m) \tag{3}$$

where $u_j^{\max}$ and $u_j^{\min}$ are the upper and lower bounds of control forces of the jth device, respectively.

N_j is jth device's number of trial control force.

Then, at a time, only one trial control force is randomly selected from each device's control force set, therefore one combination of control force vector at time instant t_s can be obtained:

$$\{\bar{u}_s\} = \{\bar{u}_1, \bar{u}_2, \ldots, \bar{u}_m\} \tag{4}$$

The total number ($\mathbf{S}$) of all combinations of trial control forces at time instant t_s becomes

$$\mathbf{S} = \prod_{j=1}^{m} N_j \tag{5}$$

The state vector of the structure, the control force vector and the external excitation are all known up to time t_{s-1} by installing sensors, and the external excitation at time instant t_s is supposed to be equal to that at time instant t_{s-1}. ($\{f_{s-1}\} = \{f_s\}$). Since the control force vector at time

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instant t_s has been assumed as the above mentioned **S** combinations, corresponding **S** combinations of state vector should be obtained at time instant t_s. The Runge–Kutta fourth-order scheme is used to determine each combination of state vector $\{\bar{X}_s\}$.

$$\{\bar{X}_s\} = \{X_{s-1}\} + \tfrac{1}{6}(\{K_0\} + 2\{K_1\} + 2\{K_2\} + \{K_3\}) \tag{6}$$

in which: $\{K_0\} = \Delta t([A]\{X_{s-1}\} + [B]\{u_{s-1}\} + [D]\{f_{s-1}\})$

$$\{K_1\} = \Delta t([A](\{X_{s-1}\} + \tfrac{1}{2}\{K_0\}) + [B]\{u_{s-1/2}\} + [D]\{f_{s-1/2}\})$$

$$\{K_2\} = \Delta t([A](\{X_{s-1}\} + \tfrac{1}{2}\{K_1\}) + [B]\{u_{s-1/2}\} + [D]\{f_{s-1/2}\})$$

$$\{K_3\} = \Delta t([A](\{X_{s-1}\} + \{K_2\}) + [B]\{\bar{u}_s\} + [D]\{f_s\})$$

$$\{u_{s-1/2}\} = \tfrac{1}{2}(\{u_{s-1}\} + \{\bar{u}_s\}), \quad \{f_{s-1/2}\} = \tfrac{1}{2}(\{f_{s-1}\} + \{f_s\}).$$

In order to maintain human comfort or occupation amenity, the authors intend to minimize the vibration energy of the main structure at time instant t_s. The 'discrete-index function', $\bar{J}_s$ is defined as Equation (7)

$$\bar{J}_s = \tfrac{1}{2}\{\bar{X}_s^*\}^{\mathrm{T}} \begin{bmatrix} \mathbf{M}^* & \mathbf{0} \\ \mathbf{0} & \mathbf{K}^* \end{bmatrix} \{\bar{X}_s^*\} \tag{7}$$

in which, $\{\bar{X}_s^*\}$ is $(2n \times 1)$ state vector at time instant t_s excluding the additional mass (where the supercript means the additional mass will not be taken into account); $[M^*]$ and $[K^*]$ are $(2n \times 2n)$ mass matrix and stiffness matrix, respectively.

It has been investigated that compared to the people in an office or residential environment, people involved in an activity such as aerobics may be comfortable with a higher level acceleration [9]. Since the additional mass is the place where human movement occurs, we think that the vibration of the additional mass would not influence the occupation amenity under the investigated vibration level. So the vibration of the additional mass is not evaluated in the 'discrete-index function'.

The value of $\bar{J}_s$ for all combinations of $\{\bar{u}_s\}$ can be calculated. The most adequate combination of trial control forces are determined as the real control force at time instant t_s by finding out the typical combination which makes the discrete-index function $\bar{J}_s$ minimum.

The process of the 'Discrete-Optimizing Control Method' can be written as follows:

⟨Discrete-Optimizing Control Algorithm⟩

(1) Get information of external excitation and state vector at time instant t_{s-1} from sensors, and suppose the external excitation at time instant t_s equal to that at time instant t_{s-1}.
(2) Assume the set of trial control forces $\langle \bar{u}_j \rangle$, in which each element of $\langle \bar{u}_j \rangle$ should be within the capacity of control device. All combinations of control force vector $\{\bar{u}_s\}$ at time instant t_s can be obtained.
(3) Predict controlled state vector $\{\bar{X}_s\}$ at time instant t_s from all combinations of $\{\bar{u}_s\}$ by Equation (6)
(4) Calculate all values of $\bar{J}_s$ from all combinations of $\{\bar{X}_s\}$ by Equation (7)
(5) Determine one combination of control forces which makes the discrete-index function $\bar{J}_s$ minimum as the real control force vector at time instant t_s.

The flow chart of the 'Discrete-Optimizing Control Method' is shown in Figure 4.

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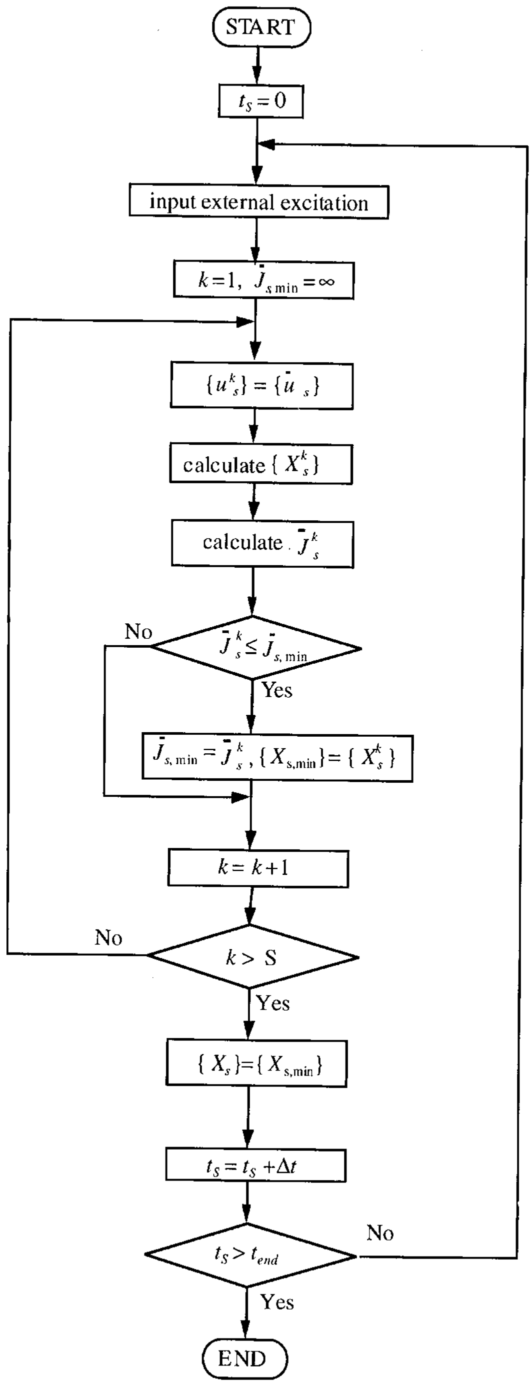


Figure 4. Flow chart of the Discrete-Optimizing Control Method.

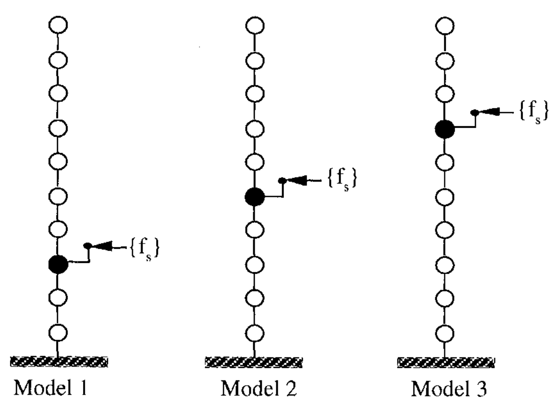
The discrete-index function $\bar{J}_s$ is not calculated upon the continuously predetermined control force $\langle \bar{u}_j \rangle$, and so the selected control forces may not probably be the exact optimum value. But it is considered to be the most agreeable value to the real optimum value. When using the 'Discrete-Optimizing Control Method', control forces will never exceed the capacity of control devices, and no complicated mathematical technique is needed; only knowledge about numerical response analysis is required.

3. NUMERICAL SIMULATIONS

3.1. External excitation and analysis model

This paper focuses on the structure's response caused by rhythmic human movements, in order to resemble the practical problem, the external excitation is assumed to be impulsive as shown in Figure 5(b) according to the practical investigated results. Considering the rhythm of the real aerobics exercises, the period of the external excitation is assumed to be 0.8 sec. In order to figure out the basic character of the structure's response due to the impulsive excitation, the sinusoidal excitation whose period is the same as the impulsive excitation is also investigated in this paper (Figure 5(a)). The Fourier spectrum of the two kinds of excitations are also shown in Figures 5(c) and 5(d). Assuming that the average powers of the two kinds of excitations is approximately the same, the amplitudes of the sinusoidal and impulsive excitation are taken as 5 and 20 tonf.

The analysis model is assumed to be a 10-storey steel structure with an additional mass connected to different intermediate stories. The external excitation is assumed to act on the additional mass horizontally. Model 1 is the structure with the additional mass connected to the third floor; model 2 is the structure with the additional mass connected to the fifth floor, and model 3 is the structure with the additional mass connected to the seventh floor.



The storey-weight and stiffness of the main structure are given in Table I. The inner viscous damping is considered to be proportional to the stiffness, and the damping factor for the 1st model of undamped vibration is assumed to be 2 per cent. Table II shows the natural period and the natural frequency of the structure.

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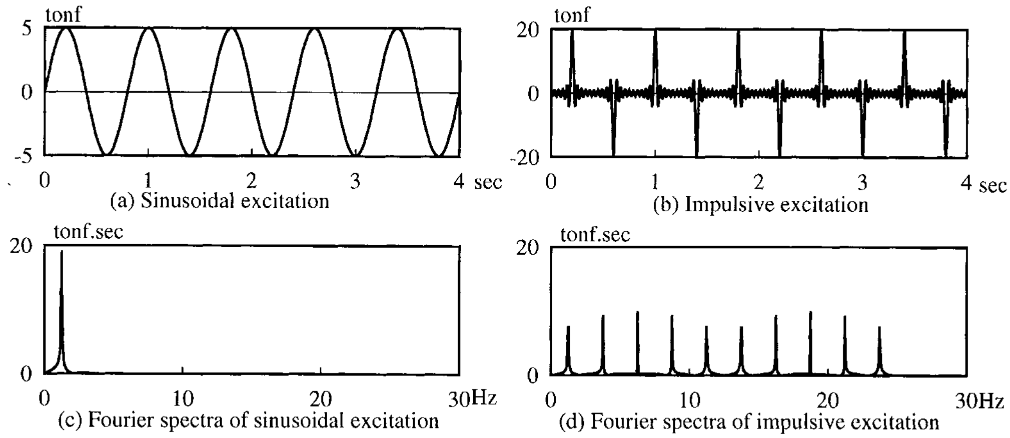

Figure 5. Horizontal excitation: (a) sinusoidal excitation; (b) impulsive excitation; (c) Fourier spectra of sinusoidal excitation; (d) Fourier spectra of impulsive excitation.

Table I. Specification of structure.

Storey	1	2	3	4	5	6	7	8	9	10
Weight (tonf)	1010	810	810	610	610	610	600	600	600	600
Stiffness (tonf/cm)	1070	870	870	760	700	680	640	630	615	590

Table II. Dynamic properties of structure.

	First	Second	Third	Fourth	Fifth
Natural period (s)	1.17	0.43	0.27	0.19	0.16
Natural frequency (Hz)	0.85	2.33	3.70	5.26	6.25

While the weight of the additional mass m_{d} is assumed to be 400 tonf, its stiffness k_{d} and damping coefficient corresponding to the connected floor c_{d} are 100 tonf/cm and 0.6, respectively. In this paper, since the structure's vibration level is quite low, analysis is carried out within the elastic region. The Runge–Kutta fourth-order scheme is used in numerical response analysis. Duration time of analysis is 10 sec. Time interval of analysis is 0.005 sec. The properties of the structure and the additional mass are kept constant throughout the time period under investigation.

3.2. *Active control device*

Active mass damper is used to execute the control force. As shown in Figure 6, each active mass damper is assembled by an auxiliary mass m, an AC servo motor, ball screw shaft, and a vibration sensor. The AC servo motor is assumed to be the acceleration controlled type. The relative acceleration between the auxiliary mass m and the corresponding floor is observed by the

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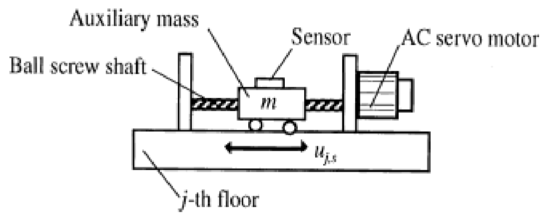

Figure 6. Active mass damper.

vibration sensor step by step. Since the control force is the reaction force to the inertia force of the auxiliary mass,

$$u_{j,s} = -\alpha_s m$$

where $u_{j,s}$ is the jth floor's control force at time instant t_s. α_s is the relative acceleration between the jth floor and the auxiliary mass m. The command signal is transmitted to the motor by regulating the relative acceleration α_s, so the control force $u_{j,s}$ can be obtained instantly.

Since the control force is defined within a certain bound, $u_j^{\max} < u_{j,a} < u_j^{\min}$, the capacity of the control device can be guaranteed with a suitable value of the auxiliary mass m. The vibration of the auxiliary mass does not influence the occupation amenity of the whole structure, it will not be further discussed in this paper.

3.3. Response of non-control structure

The response of the uncontrolled structure is conducted with two kinds of excitation, using the above-mentioned models 1–3. Figure 7 shows the maximum acceleration response for each floor.

In the case of the sinusoidal excitation, though the external excitation is located on different intermediate floors of the structure, the maximum acceleration responses for each floor are approximately the same. The maximum absolute acceleration of model 1 ranges from 0.829 to 4.205 cm/sec^2, the maximum absolute acceleration of model 2 ranges from 0.789 to 4.868 cm/sec^2, and the maximum absolute acceleration of model 3 ranges from 0.557 to 4.493 cm/sec^2.

In the case of the impulsive excitation, except for the floor where the external excitation is located, only a little difference exists among the maximum acceleration response for other floors. The maximum absolute acceleration of model 1 ranges from 1.507 to 3.794 cm/sec^2, the maximum absolute acceleration of model 2 ranges from 1.396 to 3.116 cm/sec^2, and the maximum absolute acceleration of model 3 ranges from 1.332 to 3.399 cm/sec^2. The authors consider that the location of the external excitation only affected the response of the whole structure to a limited degree.

The top floor's time history of absolute acceleration response is shown in Figure 8. The time history of absolute acceleration response due to impulsive excitation is quite similar to the recorded result, we think the selected external excitation is reasonable.

3.4. Top-floor control

In general, for a shear-type building under earthquake excitation or wind excitation, the first modal response is the primary one, and the responses at the top floor is the peak one. Therefore, if the responses at the top floor of the building is suppressed, the responses of the whole building

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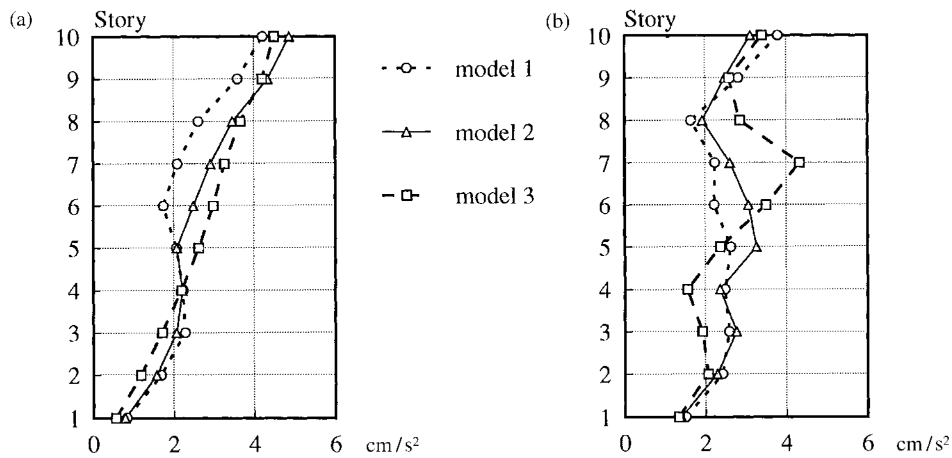

Figure 7. Maximum absolute acceleration response of non-control structure: (a) due to sinusoidal excitation; (b) due to impulsive excitation.

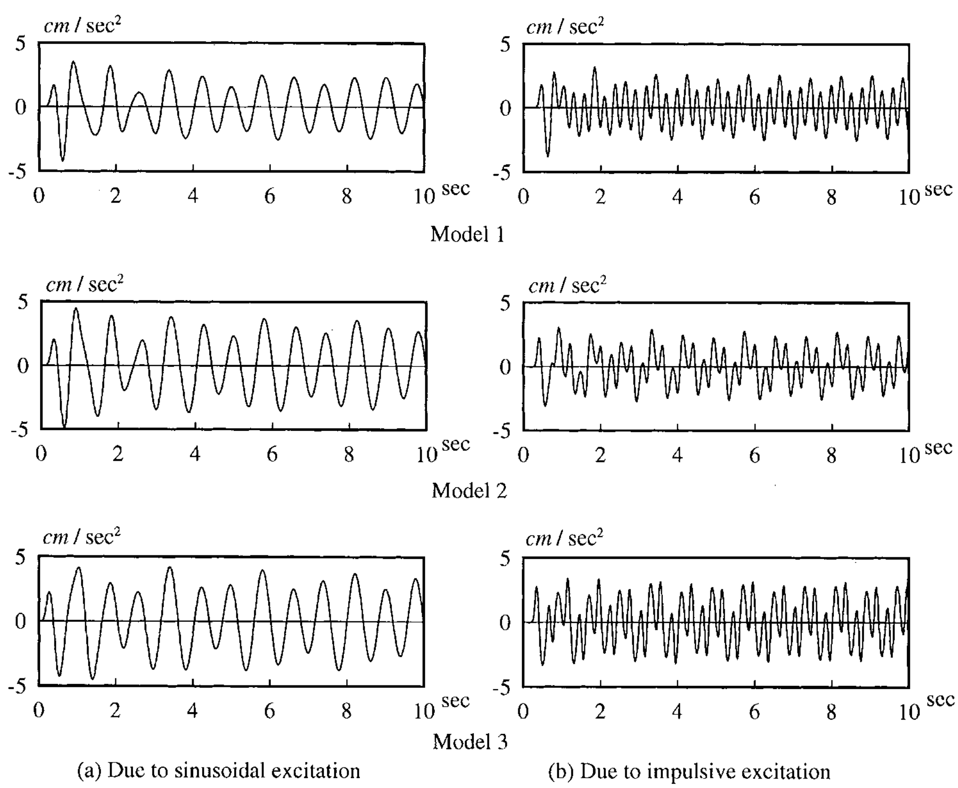

Figure 8. Top-floor's time history of absolute acceleration response under non-control condition: (a) due to sinusoidal excitation; (b) due to impulsive excitation.

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should be controlled. For the consideration of actual engineering application, first of all, model 1 is used to investigate the response reduction with active control device only installed on the top floor of the building.

The influence of the capacity of the control device as well as the number of trial control forces are also investigated here. The sets of control forces are first designed with the number of trial control forces N_j equal to 3.

$$\text{type 1: } \langle \bar{u}_{10} \rangle = \{-1.0, 0.0, 1.0\} \quad \text{(tonf)} \tag{8a}$$

$$\text{type 2: } \langle \bar{u}_{10} \rangle = \{-2.0, 0.0, 2.0\} \quad \text{(tonf)} \tag{8b}$$

$$\text{type 3: } \langle \bar{u}_{10} \rangle = \{-3.0, 0.0, 3.0\} \quad \text{(tonf)} \tag{8c}$$

Figure 9 shows the maximum values of acceleration at each floor of these three types. In both the sinusoidal excitation and the impulsive excitation cases, little response reduction can be seen through the entire structure, and except for in the lower floors, responses are enlarged, especially when the capacity of control force is getting larger. It is clear that the whole structure has been stimulated by the relatively large amount of control force which has been introduced into the structure.

The sets of control forces are then designed with the capacity of the control device equal to 2 tonf and the number of trial control forces N_j is selected to be equal to 3, 5 and 9:

$$\text{type 2: } \langle \bar{u}_{10} \rangle = \{-2.0, 0.0, 2.0\} \quad \text{(tonf)} \tag{8b}$$

$$\text{type 4: } \langle \bar{u}_{10} \rangle = \{-2.0, -1.0, 0.0, 1.0, 2.0\} \quad \text{(tonf)} \tag{8d}$$

$$\text{type 5: } \langle \bar{u}_{10} \rangle = \{-2.0, -1.5, -1.0, -0.5, 0.0, 0.5, 1.0, 1.5, 2.0\} \quad \text{(tonf)} \tag{8e}$$

Figure 10 shows the maximum values of acceleration at each floor of these three types. In both the sinusoidal excitation and the impulsive excitation cases, the response reduction effects are exactly the same among these three types. Since an increasing number of trial control forces will

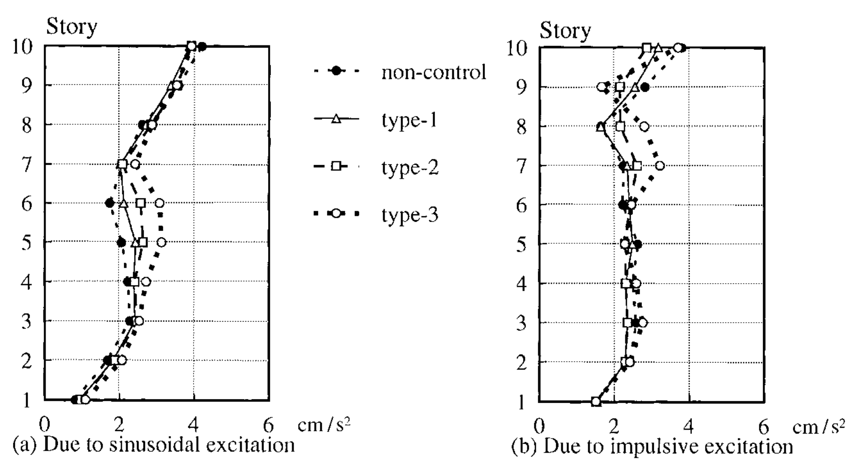

Figure 9. Maximum absolute acceleration response of top-floor control structure ($N_j = 3$): (a) due to sinusoidal excitation; (b) due to impulsive excitation.

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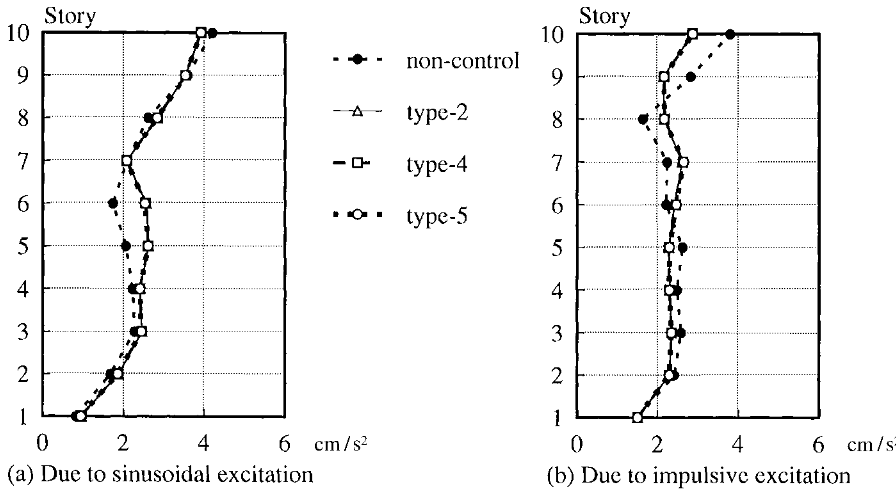

Figure 10. Maximum absolute acceleration response of top-floor control structure (capacity of control device = 2 tonf): (a) due to sinusoidal excitation; (b) due to impulsive excitation.

obviously increase the real computing time, and it only influences the response reduction effect of the whole structure by a small degree, the following analyses will be conducted with the number of trial forces equal to 3.

The response of the structure as a whole cannot be reduced, hence the authors do not consider it to be a good way to control the whole structure with the control device only installed on the top-floor. In the following section, active vibration control will be conducted with multiple active control devices installed on different floors of the structure.

3.5. Selected floor control

In this paper, active control devices are designed to be installed into the building structure in three ways. The first way is an active vibration control system with control devices installed on each floor of the structure and named as full-floor control; the second way is an active vibration control system with control devices installed on three floors, the same floor where the external excitation occurs and the upper and lower adjoining floors, and named as concentrated three-floor control; And the third way is an active vibration control system with control device only installed on the floor where the external excitation occurs, and named as one-floor control.

3.5.1. Identical control devices. At first, numerical analysis is carried out under the assumption that active control devices used in each case are identical. Model 1 is analysed with the capacity of each control device being 2 tonf, model 2 is analysed with the capacity of each control device being 1 tonf, and model 3 is analysed with the capacity of each control device being 0.5 tonf. The maximum absolute acceleration responses are shown in Figures 11.

When the capacity of each control device is 0.5 tonf (Figure 11(A)), little response reduction effect can be obtained through the entire structure in both the sinusoidal excitation and the impulsive excitation cases no matter how the active control devices be installed, especially when

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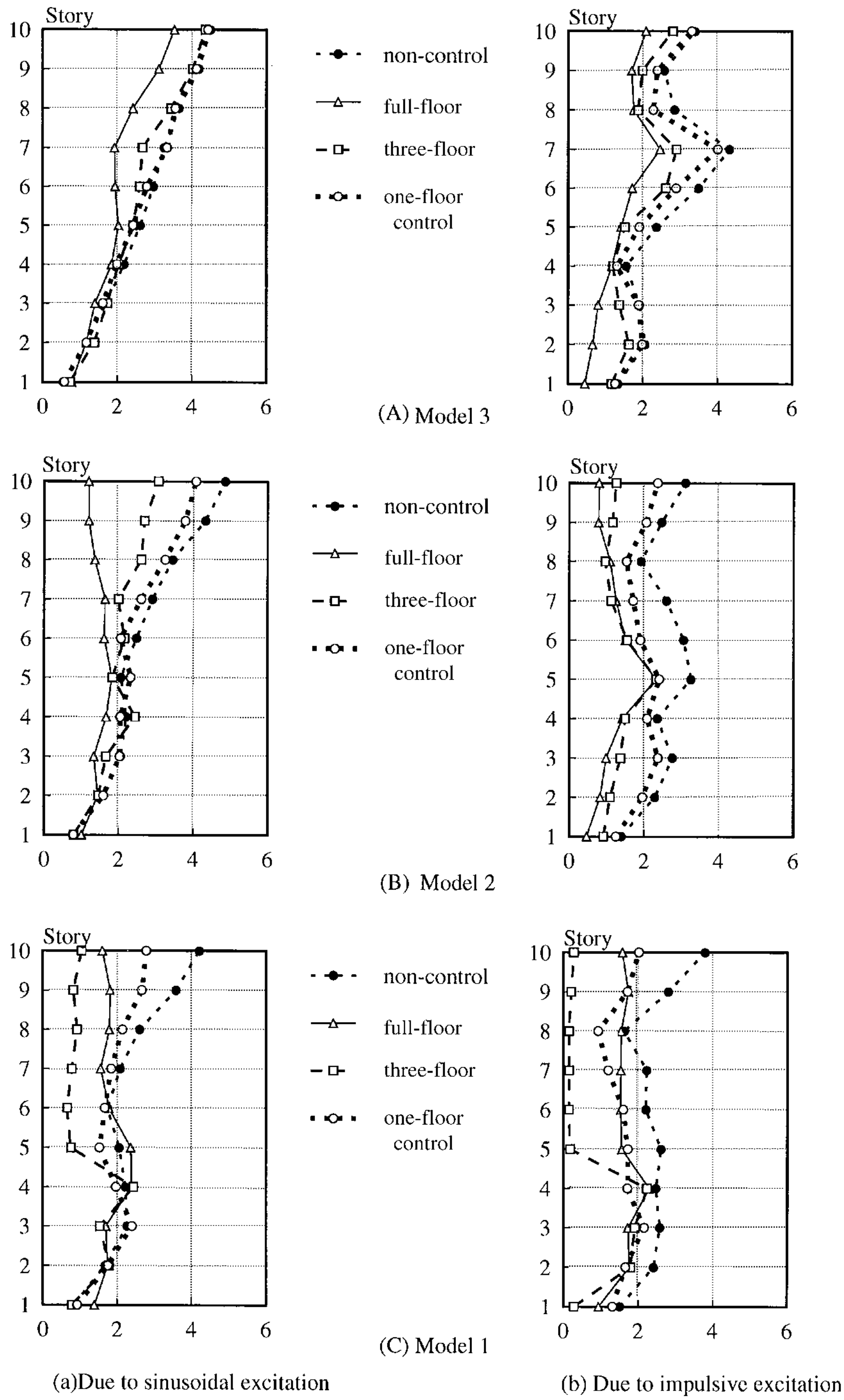

Figure 11. Maximum absolute acceleration response with identical control device: (a) due to sinusoidal excitation; (b) due to impulsive excitation.

one-floor control is used. Compared to others, the effectiveness of full-floor control is a little bit better.

When the capacity of each control device is 1 tonf (Figure 11(B)), in the case of the sinusoidal excitation, acceleration responses are only reduced on the upper floors with the control devices installed in the above mentioned three ways, the ratios compared to the non-control condition on the top floor are 0.25 (full-floor control), 0.63 (three-floor control) and 0.84 (one-floor control). In the case of the impulsive excitation, response reduction effects can be obtained through the entire floor with full-floor control or three-floor control. Little reduction can be obtained with one-floor control. And the ratios compared to the non-control condition on the top floor are 0.25 (full-floor control), 0.40 (three-floor control) and 0.76 (one-floor control).

When the capacity of the control device is 2 tonf (Figure 1(C)), the response reduction effects of three-floor control are significant and apparently better than the effects of others on the upper floors. The ratios compared to the corresponding non-control condition on the top floor are 0.25 in the case of the sinusoidal excitation and 0.07 in the case of the impulsive excitation. But hardly any reduction effects can be obtained on the floors where control devices have been installed. The effectiveness of one-floor control is getting better according to the increasing of control force, but still not as good as that of three-floor control. In both the sinusoidal excitation and the impulsive excitation cases, the response reduction effects of full-floor control can only be obtained on the upper storeys.

Compared to full-floor control, three-floor control develops full effectiveness with little number of control devices. But if the installation of control devices is limited to the floor where the external excitation occurs, since the total amount of control forces introduced into the structure is small, expected response reduction effects cannot be obtained.

3.5.2. Approximately identical total amount of control forces. Then numerical analysis is carried out under the assumption that the total amount of the capacity of all active control devices are approximately equal. For full-floor control, the capacity of each control device is 0.5 tonf, so the total amount of control force is equal to 5 tonf. For three-floor control, the capacity of each control device is 2 tonf, so the total amount of control force is equal to 6 tonf. For one-floor control, the capacity of each control device is 5 tonf, so the total amount of control force is equal to 5 tonf. The maximum absolute acceleration responses are shown in Figures 12 using models 1–3.

Similar tendency can be seen in models 1–3. Except for the floor where external excitation occurs, responses of the structure are reduced if active control devices are introduced into the structure. The effects of three-floor control and full-floor control are almost equal and obviously better than that of one-floor control, although the structure is controlled by an approximately identical total amount of control forces. On the floor where external excitation occurs, stimulated by a relatively large amount of control force, the response of one-floor control is enlarged almost two times compared to the non-control condition.

Compared to one-floor control or full-floor control, three-floor control is found to be the most reasonable method with the control devices installed concentrated in the adjacent three floors of the vibration source.

3.5.3. Effective location of control devices. Although response of the whole structure can be effectively reduced by three-floor control, response reduction effects on the floors where control devices installed are not so good compared to the other floors. Based on the analysis result deduced from one-floor control, responses on these floors cannot be further reduced by increasing

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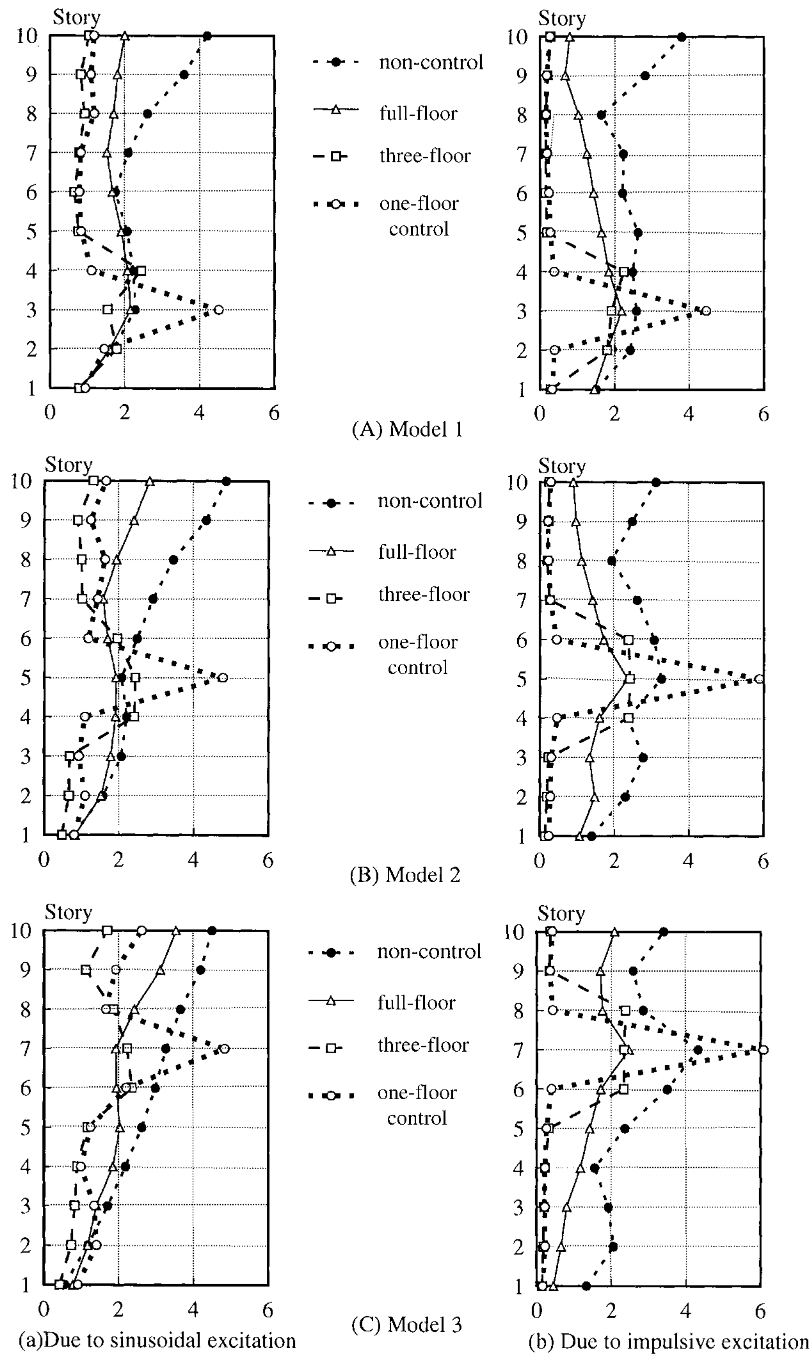

Figure 12. Maximum absolute acceleration response with approximately identical total amount of control force: (a) due to sinusoidal excitation; (b) due to impulsive excitation.

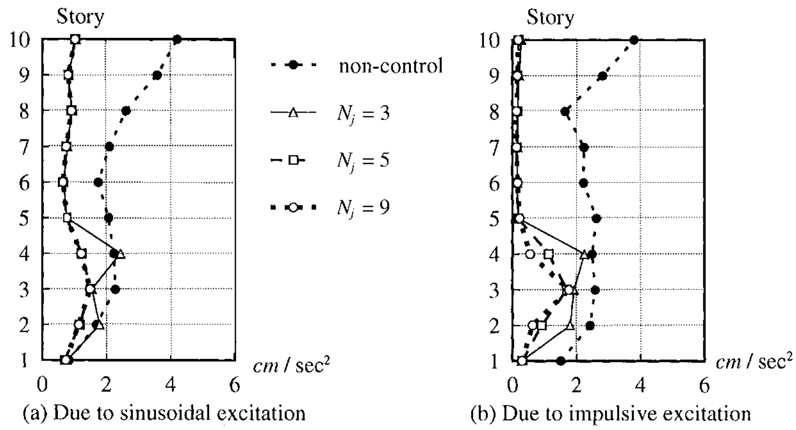

Figure 13. Maximum absolute acceleration response (capacity of control devices = 2 tonf): (a) due to sinusoidal excitation; (b) due to impulsive excitation.

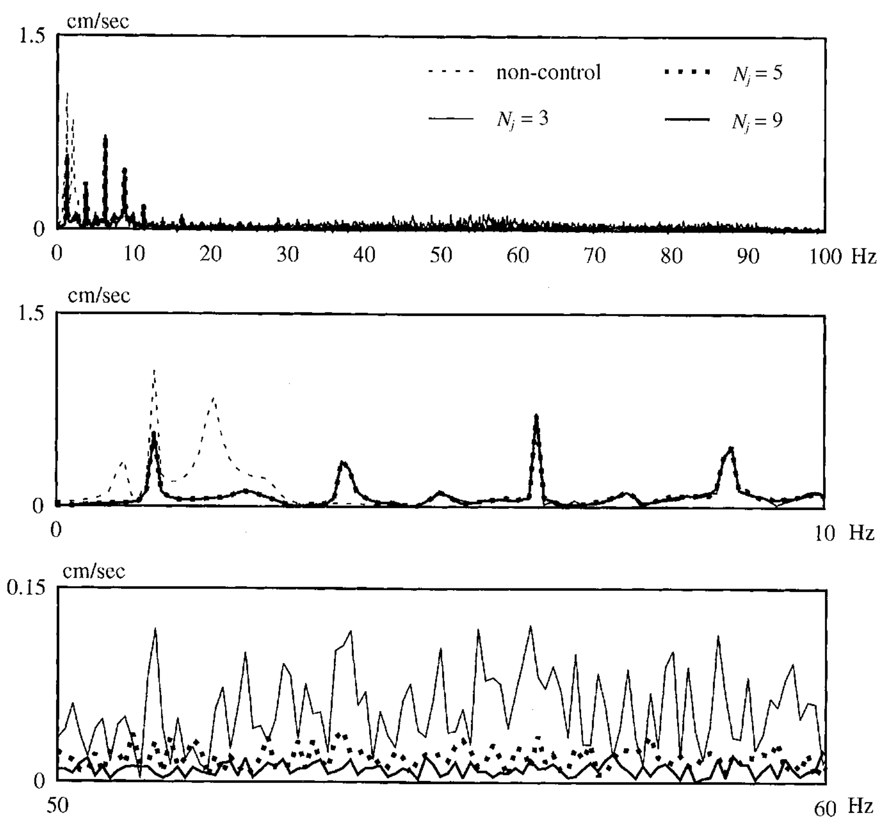

Figure 14. Fourier spectra of third floor's absolute acceleration response (due to sinusoidal excitation).

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the capacity of control devices. In order to solve this problem, active vibration control is carried out with the capacity of control devices being 2 tonf, and the number of trial forces being 3, 5 and 9. Figure 13 shows the maximum absolute acceleration response. Responses on the floors where control devices had been installed are clearly reduced by increasing the total number of trial forces.

In this paper, Fourier spectra of absolute acceleration response on the third floor caused by the sinusoidal excitation is shown in Figures 14. Compared to the non-control condition, the amplitudes of controlled structure are obviously reduced at the dominant frequency, but enlarged at the high frequency ranges. Because the capacities of control devices are identical, only slight differences can be seen among the reduced amplitudes of the controlled structure at the dominant frequency, no matter how large the number of trial forces is. On the other hand, the enlargements at high frequency ranges are decreased with an increasing total number of trial control forces.

Similar tendency can be seen when external excitation is impulsive.

It is clear that the response reduction effect of the whole structure is principally determined by the capacity of the control device, and the effectiveness on the floors where control devices had been installed can be improved by increasing the total number of trial forces.

4. CONCLUSION

In this paper, based on the numerical analysis of the horizontal external excitation acting on an intermediate story, the following conclusions are drawn:

(1) The Discrete-Optimizing Control Method is proved to be an effective control method through numerical simulation.
(2) The responses of the whole structure cannot be reduced with a control device installed only on the top floor.
(3) Responses of the whole structure can be effectively reduced with the control devices concentrated on the adjacent three floors of the vibration source.

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